Power Flow Control Through Topology Optimization Software: Applications and Case Studies

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Current Congestion Management Impacts

Annual US Impacts

- Costs: $4-8 billion
- Reliability: overloads 5-20% of the time
- Wind and Solar: 2-17% curtailments

Example from Southwest Power Pool

SPP Power Prices
March 10, 2018, 20:10 CST

Price Scale

- $600/MWh
- $300/MWh
- $100/MWh
- $40/MWh
- $0/MWh
- < -$10/MWh

Wind curtailments
Negative price: ($29/MWh)
Transmission line carry more flow than it safely can (contingency overload, breach)
Topology Optimization Software

Automatically finds reconfigurations to route flow around congested or overloaded elements ("Waze for the grid")

Historical Condition
Congestion + Overload

NewGrid Router Topology Optimization Software

"Open/Close Circuit Breakers X and Y"

With Reconfiguration
Flow Diverted
No Congestion or Overload
7-bus Example: All Lines Closed

Case Hourly Cost: $18,186
7-bus Example Results: Before & After

Before: all lines Closed

- Hourly Cost
  - All lines Closed: $18,186
  - Line 3-4 Opened: $17,733
  - Savings: $453 (2.5%)

<table>
<thead>
<tr>
<th>Generation</th>
<th>All lines closed</th>
<th>Line 3-4 open</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus 1</td>
<td>80 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td>Bus 2</td>
<td>220 MW</td>
<td>296 MW</td>
</tr>
<tr>
<td>Bus 4</td>
<td>6 MW</td>
<td>0 MW</td>
</tr>
<tr>
<td>Bus 6</td>
<td>188 MW</td>
<td>220 MW</td>
</tr>
<tr>
<td>Bus 7</td>
<td>291 MW</td>
<td>270 MW</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>785 MW</strong></td>
<td><strong>786 MW</strong></td>
</tr>
</tbody>
</table>
Reconfiguration Practice

**Traditional/Today**
- Employed on an ad-hoc basis
- Reconfigurations are identified based on staff experience
- Reconfiguration development is a time-consuming process
- The transmission grid flexibility is underutilized

**With Topology Optimization**
- Software identifies reconfiguration solution options to select
- Fast identification: 10 s – 2 min
- Facilitate training of new operators
- Take full advantage of grid flexibility
- Achieve better outcomes
Topology Optimization Architecture

**Optimization**
- Topology Optimization
  - Topology Optimization output:
    - Topology (reconfiguration)
    - Dispatch Commitment
    - Marginal Costs

**Feasibility (Reliability)**
- Contingency Evaluation
  - Contingency Assessment outputs:
    - Feasible/Infeasible optimized state
    - Constraints to Ensure Feasibility of the optimization outcome
Applications

**Business Process**
- Long-term planning
- Seasonal contingency planning
- Outage coordination
- Day-ahead market optimization
- Real-time market optimization
- Intra-day operations

**Objectives**
- Adapt grid to emergency system conditions
- Increase grid resilience
- Avoid load shedding
- Enable conflicting outages
- Train new staff
- Increase transfer capability
- Relieve flow violations
- Minimize congestion costs
- Reduce wind curtailments
Case Studies Overview
Topology optimization software finds highly beneficial reconfigurations

1. **Long-Term Planning in SPP**
   - Avoided load shedding for severe NERC TPL-001 planning events (P6, P7 and Extreme Events).

2. **Contingency Mitigation Plan in ERCOT**
   - Identified new plan that avoids load shedding (Ref. [1]).

3. **Additional Transfer Capacity under Outages in National Grid UK**
   - Increased transfer capability 3-12% for critical constraints under severe outages (Ref. [2], [3]).

4. **Congestion, Overload and Wind Curtailment Relief in SPP Operations**
   - Full overload and wind curtailment relief under recent real-time conditions.

5. **Congestion Cost Relief in PJM Real Time Markets**
   - Co-optimization of topology and dispatch provides 40-70% congestion cost relief (Ref. [10]).

Other analyses to date:
- ERCOT Relief of most frequent market constraint in 2014-2015 (Appendix, Ref. [4]).
- PJM operations: Relief of critical historical base-case overloads (Ref. [10]).
- PJM DA markets: 30-50% congestion cost relief, 2010 conditions (Ref. [6]).
- PJM high renewables: Reduced curtailments under 30% penetration case (Ref. [12]).
- PJM outage coordination: overload and congestion relief (EMS cases).
Case Study 1: SPP Long Term Planning

Avoiding Non-Consequential Load Loss in Planning

• NERC allows load shedding as part of the Corrective Action Plan (CAP) for specified planning events involving multiple transmission outages that would otherwise result in NERC TPL-001-4 violations.*

• SPP identified three severe multiple-contingency events** (P6, P7 and Extreme) for which the CAPs rely on substantial load shedding (re-dispatch is ineffective).

• We found corrective reconfigurations for all three cases that relieve the violations without load shedding and without causing other violations.

* NERC Standard TPL-001-4 — Transmission System Planning Performance Requirements.
** P6 Events involve two sequential, overlapping single contingencies. P7 Events are multiple contingency as a result of a common structure or other single failure. Extreme Events include loss of a transmission corridor, of an entire substation or power plant, or of multiple elements due to a regional event or critical cyber attack. See NERC Standard TPL-001-4.
### Case Study 1: SPP Long Term Planning

#### Avoiding Non-Consequential Load Loss in Planning

<table>
<thead>
<tr>
<th>Case Study Type</th>
<th>Flow on Violated Branch</th>
<th>Avoided Load Loss</th>
<th>No. of Actions</th>
<th>No. of New Constraints</th>
<th>Radialized Load</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial [% of Rating]</td>
<td>With Solution [% of Rating]</td>
<td>[MW]</td>
<td>&gt;95% flow</td>
<td>&gt;100% flow</td>
</tr>
<tr>
<td>P6 Event</td>
<td>129%</td>
<td>86%</td>
<td>243</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>P7 Event</td>
<td>107%</td>
<td>94%</td>
<td>55</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Extreme Event</td>
<td>113%</td>
<td>97%</td>
<td>151</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

- **Flow on Violated Branch**
  - Initial: The flow on the violated branch before applying any solution.
  - With Solution: The flow on the violated branch after applying the solution.
- **Avoided Load Loss**: The load loss avoided due to the application of solutions.
- **No. of Actions**: The number of actions taken to address the issues.
- **No. of New Constraints**: The number of new constraints added to the system.
- **Radialized Load**: The load radialized by the application of solutions.

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**Cases and Events**

- **P6 Event**: 129% initial flow, 86% with solution, 243 MW avoided load loss, 2 actions, 1 new constraint, 0 radialized load.
- **P7 Event**: 107% initial flow, 94% with solution, 55 MW avoided load loss, 2 actions, 0 new constraints, 0 radialized load.
- **Extreme Event**: 113% initial flow, 97% with solution, 151 MW avoided load loss, 1 action, 1 new constraint, 0 radialized load.
Case Study 2: ERCOT Operations Planning

Avoiding Load Shedding in Contingency Plans

• “A Constraint Management Plans (CMP) is a set of pre-defined... transmission system actions... executed in response to system conditions to prevent or to resolve... transmission security violations or to optimize the transmission system.” *

• ERCOT has been using topology optimization software to support the CMP review and development since 2017.
  - In the 2017 CMP review, using topology optimization ERCOT identified an alternative to a plan that required load shedding.
  - The new plan relies on a reconfiguration and avoids customer interruptions under a transmission outage in northern Texas.
  - Helped verify that the plans selected are the most effective ones.

Case Study 3: National Grid UK Operations Planning

Increased Transfer Capability in Ops. Planning

- National Grid and Brattle studied the ability to increase transfer capability and reduce constraint management costs with topology optimization.
- Iterative collaborative analysis:
  - National Grid identified historical scenarios with active thermal limits on major (zonal) “boundary constraints.”
  - Brattle identified reconfigurations for them.
  - National Grid assessed the reconfiguration impacts and provided feedback.
- Decision variables: line switching, substation reconfigurations, phase-shifting transformer settings.

Source: Electricity Ten Year Statement 2015, National Grid, November 2015, Figure 3.1.

Grid Capacity

Congestion Savings: £14-40 million
Case Study 4: SPP Operations

Overload and Wind Curtailment Relief

SPP System Conditions
March 10, 2018, 20:10 CST

Price Scale
- $600/MWh
- $300/MWh
- $100/MWh
- $40/MWh
- $0/MWh
- < -$10/MWh

Historical Case
- Binding constraints: 3
- Shadow prices: $174 – $984/MWh
- Breached constraints: one
- Wind Curtailments: 285 MW

With Reconfigurations
- Binding constraints: 1
- Shadow price: $15/MWh
- Breached constraints: none
- Wind Curtailments: 0 MW
Case Study 5: PJM Real Time Markets

Congestion Relief in Real Time Markets

• We simulated the impacts of topology optimization on PJM RT markets.
• Models based on one operational power flow real-time snapshot per hour for three representative historical weeks of average conditions in 2010 – summer, shoulder (fall), and winter weeks. Data used from the power flows:
  – Transmission topology, branch parameters, initial voltage state.
  – External system conditions (e.g., interchange, reciprocal flowgate use).
  – Nodal load levels; unit commitment for all units.
  – Dispatch of hydro, wind, landfill, nuclear, and RMR thermal units.
• Generation economic and transmission constraint data from operations and historical market conditions.
• Model dimensions: up to 15,200 nodes and 650 dispatchable thermal PJM units, about 4,700 monitored branches and 6,100 single and multi-element contingencies.
Case Study 5: PJM Real Time Markets

Congestion Relief in Real Time Markets

Weekly Real-Time Market Congestion Cost Savings

- $8M
- $6M
- $4M
- $2M
- $0M

Production Cost Savings
Remaining Cost of Congestion

56% 32% 44% 68% 67%
Summer Winter Shoulder

50% reduction in Real Time PJM congestion costs
⇒ extrapolate to a potential for
$100 million savings in annual production costs

Increase in Weekly Energy Transfers Between PJM Regions (Summer 2010 week)

110% 111% 104%

Hourly Topology Statistics – Cumulative and Incremental (Summer 2010 week)

Total Branches
Open
Switched
Close

Switched
Open

0%
20%
40%
60%
80%
100%
Min
Median
Max

# of Branches
Conclusions

• Topology optimization software quickly identifies and evaluates viable, reliable and beneficial system reconfiguration options.

• Possible applications:
  – Quickly identify switching solutions to address reliability and congestion events efficiently.
  – Improve grid resilience by identifying reconfigurations to best deal with disruptive events.
    • Minimize the impacts by relieving overloads and consumer disconnections.
    • Expedite the recovery by providing more operational options.
  – Adapt system configuration as flow patterns change:
    • Increased wind and solar generation.
    • Retirement of legacy thermal units.
    • Manage transmission outages.
    • Address high load growth in load pockets.
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Reference Publications (I/II)


